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PROJECT APOLLO

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INTRODUCTION AND SUMMARY

The LM operational ΔV budgets for the lunar landing mission were reported on May 16, 1967 in reference 1. The rationale for the descent budget of reference 1 was essentially that reported in reference 2. However, recent developments have resulted in changes and in some cases invalidation of that rationale as well as the rationale for the ascent budget. For example, the nominal CSM/LM parking orbit altitude was lowered from 80 to 60 n. mi. by the Configuration Control Board (CCB) on November 27, 1967. Also, ground-based simulation and information obtained from the Orbiter and Surveyor missions have resulted in a reevaluation of flexibility and dispersion allowances. The purpose of this report is to present revised ΔV budgets for the LM descent and ascent (orbit insertion only) and the associated rationale which incorporate the latest developments of mission changes and knowledge of the lunar surface characteristics.

The revised LM descent and ascent ΔV budgets are 7180 and 6060 fps, respectively, for the lunar landing mission. These budgets supersede those reported in reference 3.

DESCRIPTION OF LM DESCENT AND ASCENT MANEUVERS

A sketch of the LM descent from the CSM orbit to touchdown on the lunar surface is shown in figure 1. The descent consists of a Hohmann-type orbital transfer from the 60-n. mi. circular CSM parking orbit to a pericynthion altitude of 50 000 ft. At pericynthion, the powered-descent maneuver is initiated approximately 260 n. mi. from the landing site. The powered descent consists of three operational phases - braking, final approach, and landing. The braking phase, initiated at pericynthion, is designed for efficient reduction of the orbital velocity and terminates at a position termed hi-gate. Hi-gate occurs at an altitude of approximately 9000 ft and a range-to-go of approximately 5 n. mi. The final approach phase, beginning at hi-gate, is designed to allow for pilot visual (out-the-window) assessment of the landing area and for abort safety. This phase terminates at a position termed lo-gate, which occurs at an altitude of approximately 500 ft and a range-to-go of approximately 1600 ft. The landing phase, beginning at lo-gate, is designed to provide compatibility for pilot takeover from the automatic control and to provide the capability for the crew to perform detailed visual assessment of the landing area. This phase includes a slow vertical descent from approximately 65 ft and terminates at touchdown on the surface. References 2 and 4 give further details of the powered descent. (These references assume a descent transfer from 80 n. mi.; however, the design rationale for the nominal descent is unchanged for 60 n. mi.)

A sketch of the LM powered-ascent maneuver for lunar orbit insertion is shown in figure 2. This maneuver consists of two operational phases, a vertical rise phase and a near-optimum (propellant utilization) guidance phase. The vertical rise phase is designed to establish a vertical rise for terrain clearance before pitching over for the near-optimum guidance attitude. The vertical rise is terminated on achieving an ascent rate of 50 fps. The near-optimum guidance phase is designed for efficient APS thrusting and is terminated on achieving insertion into safe orbit. Safe orbit is defined as an orbit from which (1) the active LM can complete rendezvous with the CSM using the RCS thrusters and propellant, or (2) the inactive LM can be rescued by the CSM. If the CSM is in a 60-n. mi. orbit, the LM is required to insert into a 10- by 30-n. mi. orbit. (Descriptions of the LM rendezvous and CSM rescue capabilities are beyond the scope of the present report.)

REVISED LM DESCENT ΔV BUDGET

The revised LM descent ΔV budget approved by the CCB on November 27, 1967 is shown in table I. This budget supersedes the one given in reference 3. Four types of allowances are provided for each phase of the descent. These are

(1) The nominal mission.

(2) In-flight flexibilities (for planning maneuvers in addition to the nominal).

(3) Contingencies (for abort situations).

(4) Dispersions (for off-nominal systems performance).

The phases of the descent have been described in the preceding section and in figure 1. A brief discussion of the rationale for the revised budget allowances follows.

The total LM descent ΔV budget for the lunar landing mission is 7180 fps. This budget reflects the change in CSM/LM parking orbit altitude from 80 to 60 n. mi. Further, this budget reflects a reevaluation of the dispersion analyses with current systems performance and latest knowledge of the lunar terrain characteristics established by Orbiter and Surveyor spacecrafts.

Nominal Mission

The allowance of 71 fps provides for a Hohmann-type injection from a 60-n. mi. circular CSM/LM parking orbit into a 60-n. mi. by 50 000-ft elliptical transfer orbit from which powered descent is initiated.

The braking phase allowance of 5345 fps provides for efficient reduction of the orbital velocity at pericynthion of the descent transfer to achieve the hi-gate state vector. The hi-gate state vector occurs at an altitude of approximately 9000 ft and represents the position, velocity, and acceleration required for initiating the final approach phase (ref. 4).

The allowances for the final approach and landing phases of 866 and 406 fps, respectively, provide for the remainder of the powered descent. These phases are designed to provide pilot visual (out-the-window) assessment of the approach for abort safety and for manual control of the landing. These allowances are required for satisfying the required targeting given in reference 4. The landing phase allowance provides for a nominal time of flight in this phase of 1 minute 8 seconds.

The total nominal allotment for the revised descent budget is 6688 fps.

In-Flight Flexibilities

Nominally, the LM descent maneuver is performed in the plane of the CSM orbit. Whether or not the descent occurs in plane or out of plane depends on performing the descent during the orbital revolution that carries the CSM directly over the landing site (for nonequatorial orbits). Operational flexibility is provided to permit the descent to be performed up to two revolutions earlier or later than the overhead pass. An allowance of 10 fps in the braking phase is required for the out-of-plane (0.3°) landings.

The landing site redesignation allowance in the final approach phase was originally intended to allow for gross redisignations (6000 ft) with the landing point designator (LPD) in the event large areas (or large single features) of undesirable terrain roughness were present in the landing dispersion ellipse. Analysis of recent Orbiter photographs of the lunar landing sites have shown this not to be the case. However, what is expected (based on these photos) is several craters on the order of several hundred feet in diameter randomly located within the dispersion ellipse. Therefore, it is anticipated that the LPD ~~will be used to make one to~~ three corrective maneuvers to avoid the randomly-located hazards. Based on the results of piloted analog simulations (conducted by the Guidance and Control Division) an allowance of 60 fps is ~~provided for these maneuvers. With this allo~~wance, any one of the following sets can be accomplished.

(Typical examples.)

a. Single range redesignation of 3000 ft @ 3000-ft altitude.

b. Double range redesignation: First, 2000 ft @ 5000-ft altitude.
Second, 1000 ft @ 1500-ft altitude.

c. Triple range redesignation: First, 1000 ft @ 5000-ft altitude.
Second, 1000 ft @ 3000-ft altitude.
Third, 1000 ft @ 2000-ft altitude.

A flexibility allowance is provided in the landing phase for manually maneuvering the final touchdown point to avoid terrain protuberances or craters in the immediate area of the touchdown. Also, it includes a minor allotment (less than 10 fps) for an azimuth adjustment to improve lighting conditions (sun washout phenomena, see ref. 2). Due to the random nature of the local terrain features the criteria established in simulations is translation time as opposed to a specific redesignation distance. Based on piloted analog simulations conducted to date, a time allocation of 30 seconds has proven satisfactory. However, due to the hazardous nature of this maneuver coupled with a present lack of flight simulations an additional 20 seconds for a total allowance of 50 seconds is provided (pending flight simulation experience and confidence). This requires a ΔV allowance of 265 fps for manual maneuvering as shown in table I.

Contingencies

During the descent orbit transfer, braking phase, and final approach phase, no contingencies or aborts have been identified which require additional ΔV allowances. During the landing phase, one contingency is identified. This contingency is associated with combinations of altitude and descent rate which prohibit an abort with the APS due to insufficient acceleration to prevent surface impact. When such combinations occur, the LM is committed to a single course of action - landing. The nominal descent is designed to minimize the time of flight in this no-abort region. Nominally, the no-abort region occurs during the vertical descent (below 60-ft altitude); however, under manual control, the pilot can commit to a landing anytime during the landing phase (below 500-ft altitude). Before committing to the landing, the pilot should be assured that sufficient propellant is available to do so; if not, an abort is initiated. Thus, based on fuel-gage biasing, an allowance of 40 fps is provided to null the descent rates before staging for abort.

Dispersions

The dispersion allowance provides for 3σ systems performance dispersions. Each dispersion is assumed to be independent; thus, the allowances are root sum squared (RSS). The total RSS dispersions allowance is 117 fps.

A 28-fps allowance for the orbital transfer and the braking phase is provided for dispersions up to 10 n. mi. in the CSM/LM parking orbit altitude. This altitude increase (or decrease) results from CSM dispersions in targeting the translunar midcourse corrections.

The allowances for navigation uncertainties, DPS thrust variations, and landing radar uncertainty in the braking phase are based on dispersion analyses conducted by MIT/IL reported in references 5 and 6 and unpublished studies conducted by Guidance and Control Division (GCD) and Mission Planning and Analysis Division. Terrain profiles used for landing radar updates were based on mathematical profiles and on those generated from Orbiter photographs. The 3σ DPS thrust uncertainties at FTP are +1.5 percent and -2.5 percent (ref. 7).

The 60-fps allowance for landing radar uncertainty in the landing phase provides for a slow vertical descent caused by landing radar dispersions in estimating the vertical descent rate.

The 80-fps allowance for variations in manual control techniques provides for 15 seconds variation in flight time; this allowance is based on piloted analog simulations conducted by GCD.

REVISED LM ASCENT ΔV BUDGET

(Orbit Insertion Only)

The revised LM ascent ΔV budget approved by the CCB on November 27, 1967 is shown in table II. This budget supersedes the one in reference 1. This budget provides for the same four types of allowances given for the descent: nominal, flexibility, contingencies, and dispersions. The ascent budget applies only to the main APS thrusting maneuver for launching off the lunar surface (see fig. 2) into safe orbit from which (1) the active LM can perform rendezvous with the orbiting CSM using the RCS thrusters and propellant, and (2) the inactive LM can be rescued by the CSM. (LM RCS ΔV budget requirement for completing the rendezvous is beyond the scope of the present report.)

Nominal Mission

The total LM ascent ΔV budget (orbit insertion only) for the lunar landing mission is 6060 fps. This budget reflects the change in CSM parking orbit altitude from 30 to 60 n. mi.

The nominal mission allowance of 6030 fps provides for the launch to pericynthion of a 10- by 30-n. mi. orbit. For an initial thrust-to-weight ratio of 0.32, the launch allowance includes a vertical rise until a vertical rate of 50 fps is achieved.

Flexibilities

Nominally the ascent is performed in the plane of the CSM orbit. An allowance of 20 fps is included to provide the capability of steering into the CSM orbit plane for launches occurring up to 1/2° out of plane.

Contingencies

For the CSM in an 80-n. mi. circular orbit it was required that aborts off the descent insert into a higher energy orbit (than nominal) for CSM rescue capability. If the CSM is in a 60-n. mi. circular orbit, the phasing for aborts off the descent are such that CSM rescue of the LM can be achieved from the nominal 10- by 30-n. mi. orbit. Thus, the targeting for aborts is the same as for nominal launch and no contingency allowance is required for the revised budget.

Dispersions

An allowance of 10 fps is provided for 3σ PGNCS guidance and APS thrust dispersions. No additional allowance is required for AGS guidance errors since the AGS is targeted to a standard velocity cutoff. (AGS errors will require a large allowance on the ΔV budget for rendezvous.)

CONCLUDING REMARKS

Revised LM descent and ascent (orbit insertion only) ΔV budgets for the lunar landing mission as approved by the CCB on November 27, 1967 have been presented. The revised descent budget is 7190 fps, and the revised ascent budget is 6060 fps. The budgets reflect (1) the reduction in the CSM/LM parking orbit altitude from 80 to 60 n. mi., and (2) a reevaluation of the flexibility, contingency, and dispersion allowances for the descent in view of recent information obtained from Orbiter and Surveyor missions.

TABLE I.- REVISED LM DESCENT ΔV BUDGET

[Approved by the CCB, November 1967]

Requirement	ΔV, fps				
	Descent transfer	Braking phase	Final approach phase[a]	Landing phase	Total
Nominal[b]:					
Descent from 60-n. mi. circular orbit	71	5345	866	406	6688
Flexibilities:					
Out-of-plane descent	--	10	--	--	
Landing site selection (LPD maneuvers)	--	--	60	--	335
Manual maneuvering (50-sec translation)	--	--	--	265	
Contingencies:					
Fuel gage bias for abort	--	--	--	40	
Dispersions (RSS):					
CSM orbit altitude uncertainty	13	15	--	--	
Navigation and terrain uncertainties	--	40	--	--	
DPS thrust variations	--	40	--	--	117
LR uncertainty	--	--	--	60	
Variations in manual control techniques	--	--	--	80	
Total					7180

[a] Hi-gate altitude 9000 ft.

[b] Based on maximum LM separated weight of 33 324 lb and FTP thrust of 9710 lb.

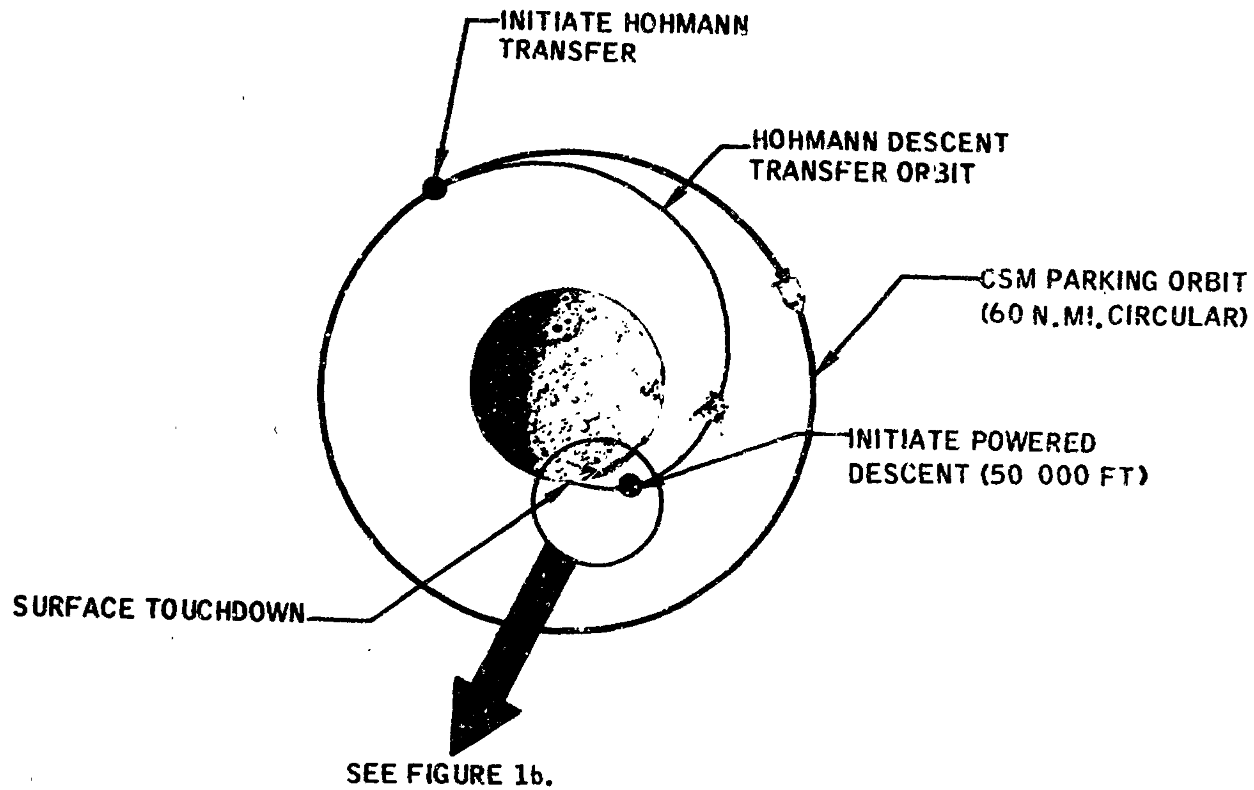
TABLE II.- REVISED LM ASCENT

(ORBIT INSERTION) ΔV BUDGET

[Approved by the CCB, November 1967]

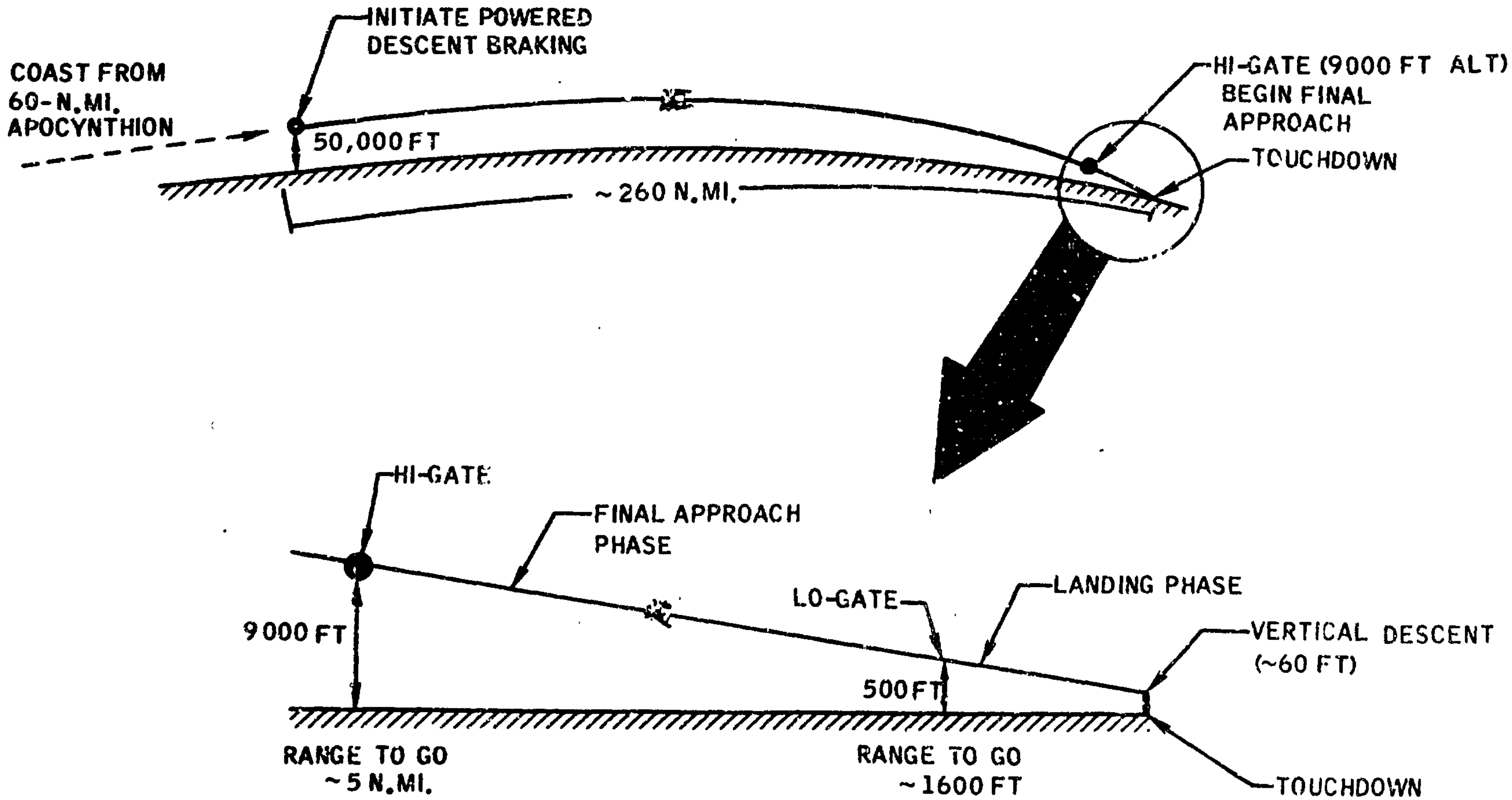
	ΔV, fps
Nominal mission[a]:	
Launch into 10- by 30-n. mi. orbit	6030
Flexibilities:	
Out-of-plane (1/2°) launch	20
Contingencies:	
None identified	0
Dispersions:	
PGNCS and APS errors	10
AGS errors	0
Total	6060

[a]Based on initial thrust-to-weight ratio of 0.33.



(a) Orbital sketch.

Figure 1.- LM descent.



(b) Powered descent phases.

Figure 1.- (concluded).

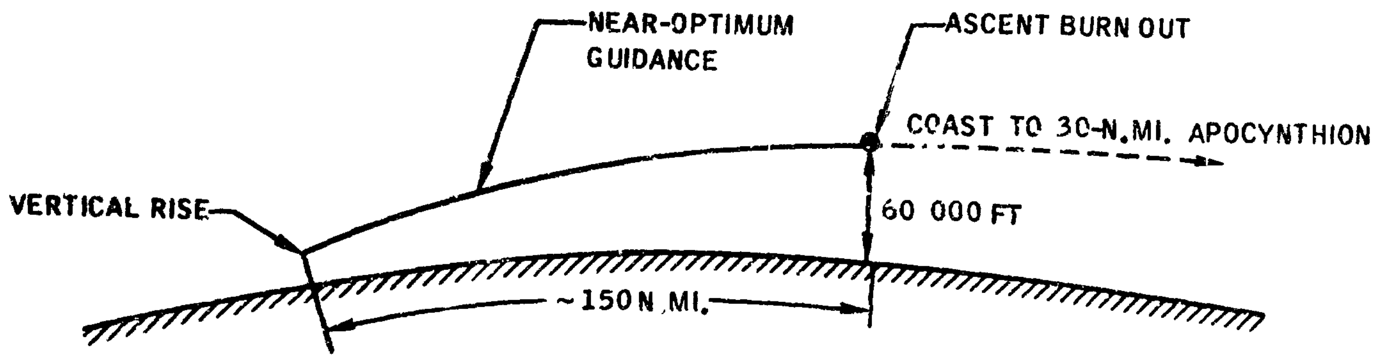


Figure 2.- LM ascent (orbit insertion only).

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